Strain and Strain Rate Gradients at the Ductile Levels of Fault Displacements

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Summary

Using the constraints imposed by observations on deep seated (ca. 30 km) zones of ductile shear displacement, an attempt is made to define a preliminary model for the initiation and growth of major ductile displacements from the initial elastic stage to a steady state configuration in which grain size reduction is a significant factor. Both theoretical and observational criteria are consistent with a significant change of width with depth.

Introduction

The recognition of linear zones, both vertical and inclined, of high ductile strains in Precambrian shield areas as the deeper tectonic expression of major fault and thrust zones has greatly improved our understanding of Precambrian history and tectonics. The potential of these zones for advancing our understanding of large scale displacement processes in general is equally great but is as yet largely unrealised. Our present knowledge of major ductile shear zones, although sufficient to allow some general statements to be made, reflects the lack of detailed field investigations on a variety of such zones which must surely be a priority for future research. The purpose of this contribution is to present a preliminary general model of a major crustal displacement zone. Such a model should incorporate data and constraints from four principal research areas (i) surface and seismic observations of neotectonic displacements, (ii) observations on fossil displacements eroded to depths of up to ca. 30 km, (iii) theoretical and experimental studies of rock deformation, (iv) crustal and lithospheric stress analysis of major displacements.

A principal objective of such a model is to highlight critical deficiencies of data or theory in any of the contributing research areas and thus to define targets for future research. In particular I am concerned to use the general statements which can be made about ductile shear zones to assist in defining the objectives for future field work on such zones.

I Ductile Shear Zones - General Statement

Large shear zones usually are easily recognised, and their limits and sense of relative displacement are easily defined. The amounts of strain and displacement are less easily defined but methods are available which allow reasonable estimates to be made if sufficiently detailed field work is carried out. No methods are available which would allow estimates of rates of strain and displacement to be made, and the timing of movements requires a better understanding of isotope behaviour than is currently available.

Even the most straightforward investigation of major shear zones is complicated by the fact that the present erosion level is likely to have represented a range of tectonic levels during the active life of the shear zone because of a) continued displacement during uplift and erosion, and b) renewed activity during later times. Bearing these problems in mind, the following generalisations seem reasonable for shear zones developing under amphibolite facies conditions in gneisses:-

(i) Shear zones from 0.5 to 40 km in width have boundary regions which are narrow relative to the total width, in contrast to small shear zones which usually have gradational boundaries. Zones with extreme grain size reduction (mylonites) are exceptional in having sharp boundaries irrespective of scale. Except in some small shear zones a central region of apparently uniform strain is present, giving a characteristic inflexion on the strain profile (see Fig. 1).

(ii) Estimates of shear strains in large shear zones give average shear strains in the region of = 4 to 6, corresponding to displacements of several tens of km in the larger zones.

(iii) Intracontinental shear zones are stress controlled, as opposed to kinematically controlled, and appear to form conjugate sets.

(iv) Significant grain size reduction accompanies the ductile deformation but mylonites are infrequent. The grain size reduction is probably the principal cause of the strain softening which allows progressive strain in the same zone, and rejuvenation of abandoned displacement zones.

(v) Variation in displacement rates can lead to ductile deformation of pseudotachylite but most pseudotachylite is relatively late and formed when the tectonic level of the zone has been reduced by uplift and erosion.

(vi) The conjugate arrangement of both small and large scale shear zones shows that shear stress must play a significant role in the initiation of shear zones.

(vii) Because of the change in temperature with depth the widths and strain profiles for a given rate of displacement will vary with depth. The strain profile at a particular depth will interact with strain profiles above and below i.e. a compatibility problem.

(viii) Models of the brittle displacement levels which assume a zero width for the underlying ductile region are unlikely to be correct.

(ix) The deformation geometry is approximately that of simple shear.

Any useful model for the ductile region of major displacements must, at least, relate width, strain rate, and strain gradient across the zone, to displacement rate - these are most easily represented and compared by reference to a strain rate profile for a particular depth. The model should be able to indicate the way in which the strain rate profile changes with depth - ideally from the surface to the base of the lithosphere.

A distinction is drawn between (i) strain rate profile during the initiation stage of the displacement and (ii) the steady state strain rate profile. Although both initiation and steady state models are discussed, observed strain profiles should ideally be the products of a steady state model. The initiation model is discussed only because the steady state model must be derived from it.

The most simple real situation is afforded by displacements with the following characteristics:-

(i) transcurrent displacement - there is ideally no displacement of horizontal isotherms and no change in crustal thickness.

(ii) kinematic control i.e. the orientation, position, direction and rate of the displacement is determined by the geometry and dynamics of a larger system e.g. the San Andreas fault, as opposed to stress controlled e.g. intraplate displacements of S.E. Asia.

Some restraints on strain rates can be established by using only the simplest of observational data available to us i.e. widths of Precambrian shear zones and displacement rates on active faults; 5 cm/yr is used because it is convenient and falls within the range of common displacement rates.

$$\dot{e} = \frac{D\,10^{-12}}{6.312W}$$

where e = strain/sec
D = displacement/yr (cm)
W = width (km)

As can be seen from the strain rate profiles in fig. 2 reasonable shear zone widths between 8 and 80 km require strain rates between 10^{-13} and Shear strains corresponding to displacements of 200 km are also shown in fig. 2 and these are within the range of observed strains in Precambrian shear zones, although the higher strains are restricted to narrow belts. The Precambrian examples suggest that a displacement of 200 km is unlikely to be accommodated in a width of less than 20 km and probably appreciably greater.

A rectangular strain profile is highly unlikely of course, and inadequate even for the limited purpose of defining a preliminary model.

III Initial Profile Model

An improvement on the rectangular profiles might be obtained if two assumptions are made:-

(i) that displacement at all tectonic levels is initially accommodated by elastic strains

(ii) that the stress distribution characteristic of the elastic displacement controls the initial ductile strains.

No convincing model exists for the initial elastic strain profile but Turcotte and Spence (1974) give a stress function for the elastic region of a simple lithospheric fault model.

$$\sigma = \frac{\pi GA}{2b} \cosh\left(\frac{\pi y}{2b}\right) \left[\left(\sinh^2 \frac{\pi y}{2b} + \sinh^2 \frac{\pi a}{2b}\right)^{\frac{1}{2}}\right]^{-1}$$

where σ = stress across the fault
y = distance from fault
b = thickness of lithospheric plate
a = thickness of elastic region
G = shear modulus
A = fault length

Although the model for which this equation is derived is not a realistic one, this is not too important so long as it is used simply to derive a range of stress profiles to assist in defining the characteristics of a stress profile which meets the observational requirements. A range of profiles derived by varying a are shown in fig. 3, in which the ordinate represents either linear stress, or linear elastic strain or strain rate. The profiles have been adjusted to represent a constant displacement, and e calibrated for this displacement to represent 5 cm/yr. The values of stress are derived from e (G = 3 x 10" dyn/cm) and represent annual increments. The internal consistency of each profile depends only on G (not corrected for pressure) and is independent of the stress function equation.

The increase in stress consequent on the increasing elastic strain would eventually be relieved by ductile strain. Ductile strain/rate profiles derived from the stress profile of Fig. 3 are shown in Fig. 4. The ductile strain rate is assumed to vary logarithmically with stress, and the profiles all adjusted to represent a displacement of 5 cm/yr.

Curves A-D have reasonable widths and strain rates but the profiles are unlike those observed in at least one important respect i.e. the absence of a central zone of relatively constant strain and the dominance of the boundary zones.

IV Growth Model

A serious shortcoming of the previous model was the implicit assumption that the transition from elastic to ductile strain is effectively instantaneous throughout the width of the shear zone. That this cannot be so is evident from the fact that the maximum annual increment of stress is about 1 bar and significant rates of ductile strain would require, say, at least 20 bars i.e. some tens of years are required before the displacement is accommodated by ductile as opposed to elastic strain.

Theoretical relationships between stress and ductile strain rate are given by White (1975). This data is for quartz only but can be used to investigate the characteristics of growth curves for ductile strain rate so long as it is borne in mind that the results are of qualitative value only when applied to rocks. The initial ductile strains in amphibolite facies gneisses of normal grain size will be accommodated by a dislocation creep mechanism, the constitutive equation for which is given by White (op. cit.).

$$e = \frac{AD_v Gb}{kT}\left(\frac{\sigma}{G}\right)^r$$

where

A = Dorn parameter		σ = differential stress	
D_v = lattice diffusivity		G = shear modulus	
b = Burgers vector		T = °K	
n = constant		k = Boltzman constant	

A constant temperature of 600°, a constant grain size of 1 m/m and a value of 4 for n (Rutter, 1975) will be used. The relationship between stress and $\dot{e}$ will be that shown in Fig. 5, which is derived from White (op. cit.), Fig. 7.

A growth model can then be constructed from annual increments of stress, by taking the total strain rate as fixed at any point within the zone.

$$\sigma_i = G.\ 2(\dot{e}_{e(1)} - \dot{e}_{d\,(i-1)}) \quad 3.1536.10^7$$

Where = stress increase in year i

$\dot{e}_{e(1)}$ = elastic strain rate in first year

$\dot{e}_{d(i-1)}$ = ductile strain rate in year (i-1)

The ductile strain rate is obtained from

$$e_{d(i)} = (f) \sum_{1}^{(i-1)}$$

No further increase in stress occurs when the stress has reached a level at which the strain is wholly ductile. Put simply, elastic strain is a mechanism for 'storing' stress and ductile strain a mechanism for relieving stress. A constant elastic strain is necessary for the steady state to be achieved. A steady state i.e. constant stress, will first be achieved in the centre of the zone and spread outwards as shown in Figs. 6 and 7. The number of years given in these figures are included only for comparative purposes and cannot be taken literally because the deformation data used is for quartz only.

Figs. 6 and 7 show significant changes during the growth stages when compared with the original profiles from which they are derived. The stage at which the growth profile reaches a steady state will depend on the precise relationship between stress and dislocation creep rates for the particular rock. The strain rate profile for the 100 year stage for profile. H is given in Fig. 8 and calibrated to a displacement rate of 5 cm/yr. This profile is beginning to resemble that of natural shear zones but we have to look to some mechanism which allows the growth to stop at this or some other intermediate stage. If growthofthe stress profile continues to completion the final ductile strain profile will replicate the elastic strain profile from which it developed.

The factor which would allow the adoption of an intermediate stage as the steady state profile is likely to be change in grain size.

V Growth Model with Change in Grain Size

An obvious but remarkable feature of shear zones is the phenomenon whereby successive strain increments are added at the sites of earlier increments even in homogeneous rocks where linear stress concentrations appear to be unlikely. This phenomenon was appropriately named 'strain softening' by Ramsay and Graham (1969). One explanation lies in the formation of stress concentrations around an original nuclear strain with subsequent development comparable with that of a crack. This explanation is less suitable for 'long term strain softening' which allows reactivation of major shear zones after lengthy periods of quiescence, although this too could be interpreted in terms of stress concentrations at the base of the brittle fault in the uppermost 15-20 km of the lithosphere.

An alternative, or possibly additional, mechanism for both short and long term strain softening is grain size reduction. Deformation by dislocation creep is accompanied by grain size reduction due to sub grain formation. This will to a certain extent be counteracted by kinematic grain recovery processes, the rate of which is stress controlled. In amphibolite facies gneisses the net effect is usually a reduction in grain size, an example of which is illustrated in Fig. 9. The grain size distributions illustrated in Fig. 9 are for tonalitic gneisses within and bordering the shear zone of Fig. 1 (a) where the position of the samples is indicated. The reduction in grain size is overall about 1.50.

Although strain rates are independent of grain size with dislocation mechanisms, this is not so for the diffusion mechanisms as can be seen for the constitutive equation for diffusional creep (White 1975).

$$e = \frac{21\, D_v\, V}{k\, T\, d^2} \left(1 + \frac{\pi \delta}{d\, D_v}\right)$$

where D_b = grain boundary diffusivity
V = activation volume
d = grain diameter
δ = grain boundary width

The effect of grain size variation is illustrated in Fig. 10 which shows the displacement in a shear zone $\gamma = 4$, with no stress gradient but a grain size variation of 1.50, under conditions where all the displacement is accomnodated by Nabarro-Herring creep. This type of strain variation occurs in some small shear zones but is unlike that of large ones. The effect of grain size variation of the amount shown in Fig. 9 would be to increase the Nabarro-Herring creep rate in the centre by a factor of 8 relative to the margin. For Coble creep where $e \; \frac{1}{d^3}$ the factor is 23. No simple relationship is to be expected between strain profile and grain size because the strain is the product of both dislocation creep which establishes the grain size, and of diffusional creep the rate of which is strongly influenced by it.

What would be the effect of grain size reduction on the growth of the strain rate profile Fig. 8? The establishment of a steady state stress and dislocation creep rate in the centre of the zone, if accompanied or followed by grain size reduction, would be modified by an increase in total strain rate at constant stress due to the introduction of a diffusional creep component. This additional component would prevent the completion of growth profile to match the original elastic strain rate profile and growth would stop at some intermediate stage. The effect of the introduction of a diffusional creep component into the 100 year profile is shown in Fig. 11 where the maximum grain size reduction is 1.50 and intermediate sizes adjusted proportionally to the stress. The more marked the grain size reduction is, the steeper is the strain gradient developed at the margin of the central part of the shear zone..

The profile shown in Fig. 8 assumes that grain size reduction takes place after about half the displacement rate is accommodated by ductile mechanisms. The rate at which grain size reduction is effected is very significant in determining the strain rate profile but unfortunately no theoretical or observational data is now available on which even a realistic guess can be made. The grain size distributions show in Fig. 9 strongly suggest that a steady state grain size was not achieved even in the highly strained centre of the shear zone. Further work is planned on this topic.

The profile shown in Fig. 8, which is a strain rate profile, would give rise to strain profiles significantly different from those shown in Fig. 1 and even more different from those believed to characterise large shear zones. A possible explanation lies in the possibility of significant grain size reduction being effected before the maximum theoretical stress is achieved, and preventing further stress increase in the centre of the zone. This would have the effect of flattening the profile in the centre of the zone. In the small shear zones shown in Figure 1 rocks corresponding to the flat part of the profile have a very uniform grain size.

VII Variation with Depth (Temperature)

An apparently paradoxical characteristic of major displacement zones is that with reduction in tectonic level the strain is increasingly concentrated in relatively zones (see Grocott 1977) even though, because of the lower temperature, the rocks deform less easily although still by ductile mechanisms. At the highest ductile levels the displacement is concentrated in relatively narrow mylonite zones, which give way upwards to brittle fracture zones with cataclasite and pseudotachylite. Mylonite zones have three characteristics, each of which is significant in terms of the growth model (i) extreme grain size reduction; (ii) extreme strain gradients at their margins; (iii) extreme shear strains within the zones.

In the growth model the time taken for strain in the centre of the zone to be wholly accommodated by ductile strain depends on the stress/ductile strain rate relationship. At lower temperatures higher stresses are required to achieve a given dislocation strain rate : from 600^o to 300^o for 1 m/m quartz the difference is about 100 bars for a strain rate of 10^{-14}. Equilibrium grain size in dislocation creep is strongly dependant on stress, higher stresses producing msaller grain sizes (White, 1976). The progressively more pronounced grain size reduction with decreasing temperature, and the correspondingly greater contribution of diffusional creep (and possibly grain boundary sliding) causes the steady state profile to be achieved at progressively earlier stages of the growth model i.e. resulting in narrow deformed zones with abrupt boundaries.

VII Width v Depth in shear zones

The growth model predicts an upwards narrowing of major ductile shear zones. Observational confirmation is limited but encouraging. In major brittle fault zones, although seismic and fault activity is spread through widths of tens of kilometres a high proportion of the displacement is concentrated on single major fractures. This would be unlikely if the ductile shear zone immediately underlying the seismic region was several tens of kilometres wide, because the compatibility problem between ductile and brittle levels would be almost insuperable. Mylonites, i.e. rocks fromed at the higher levels of ductile deformation, are characterised by much higher shear strains than the equivalent tectonites formed at deeper levels i.e. the displacement is concentrated in narrow zones at higher levels.

Finally, detailed work on the Nordre Strømfjord shear zone (Bak et. al., 1975) has shown that the boundaries of this transcurrent zone dip outwards at up to 20^{o} from the vertical

If the upward narrowing of ductile displacement zones is accepted, then the geometrical consequences must also be accepted. Of these the most significant is that the deformation must depart significantly from plane strain and the simple shear model is no longer an adequate basis for discussion. Complex strains, especially in the marginal zones, are inevitable if compatibility is to be maintained between undeformed rocks and the deformed rocks in a narrowing shear zone. This emphasises the relative lack of adequate strain data from large shear zones, because it is not known whether the predicted complex strains occur or not.

VII Conclusions ,

The semi-quantitative growth model described is consistent with many of the characteristic features of major shear zones and accounts for the change with depth of the ductile strain characteristics and products. It is emphasised that the values given for stress and time are not realistic, and are given only for comparative purposes.

The most obvious deficiencies of the model lie in the following areas:-

(i) a stress function is required which gives a better description of the initial elastic strains - this is not regarded as beingof critical significance.

(ii) stress/strain rate relationships for ductile. mechanisms are available only for quartz, calcite and olivine. Strain maps for feldspars and multicomponent materials appear to be the most vital deficiencies and are urgently required for an improved model.

(iii) a mathematically more sophisticated version of the growth model would be advantageous but is not of critical significance.

(iv) observational constraints on the model from active faults to determine the width of the shear zone at depth - this might be possible seismically by making use of the velocity anistropy due to the tectonite fabrics developed in the shear zone, together with continuous seismic reflection profiling of suitable active displacement zones.

(v) improved observational constraints by examination of ancient shear zones eroded to different levels to determine strain profiles, and systematic detailed work to determine grain size characteristics - this could lead directly to establishment of palaeo stress profiles across displacement zones.

(vi) extension of the model into the overlying levels of brittle deformation - with an improved model this might eventually be possible on a quantitative basis.

Field geologists need to provide much more observational data of a type useful for constraining the models of their geophysical and theoretical colleagues : at present the principal shortcomings are the lack of strain data, both amount and type, and grain size data across major shear zones formed at different, and known, levels in the crust.

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Text to Figures

Figure 1 (a) Strain profile of retrograded small symmetrical shear zone cutting granulite facies gneiss, Itivdleq Fjord, West Greenland. Profile derived by measurements on lithological banding of the gneiss. W, X, Y, Z show positions of specimens for which grain size data is given in Figure 9.

(b) Strain profile of retrograded slightly assymmetric small shear zone cutting granulite facies gneiss. Profile derived as in (a). Stor Ø, East Greenland.

Figure 2 Simplest strain rate profiles for possible ductile shear zones beneath fault with displacement rate 5 cm/year.

Figure 3 Stress/elastic strain rate v. distance from centre of displacement zone for various values of a (see text) Profile A, a = 2: D, a = 5: F, a = 20: H a = 40. For displacement 5 cm/yr.

Figure 4 Ductile strain rate profiles derived from figure 3 assuming logarithmic increase in strain rate with stress, and instantaneous change from elastic to ductile strain.

Figure 5 Dislocation creep strain rate v. stress for quartz, 1 m/m grain size, 600^{o}, derived from White (1976), Fig. 7.

Figure 6 Growth curves for stress distribution during transition from elastic to ductile strain, for initial stress distribution as in A, Fig. 3.

Figure 7 Growth curves for stress distribution during transition from elastic to ductile strain, for initial stress distribution as in H, Fig. 3.

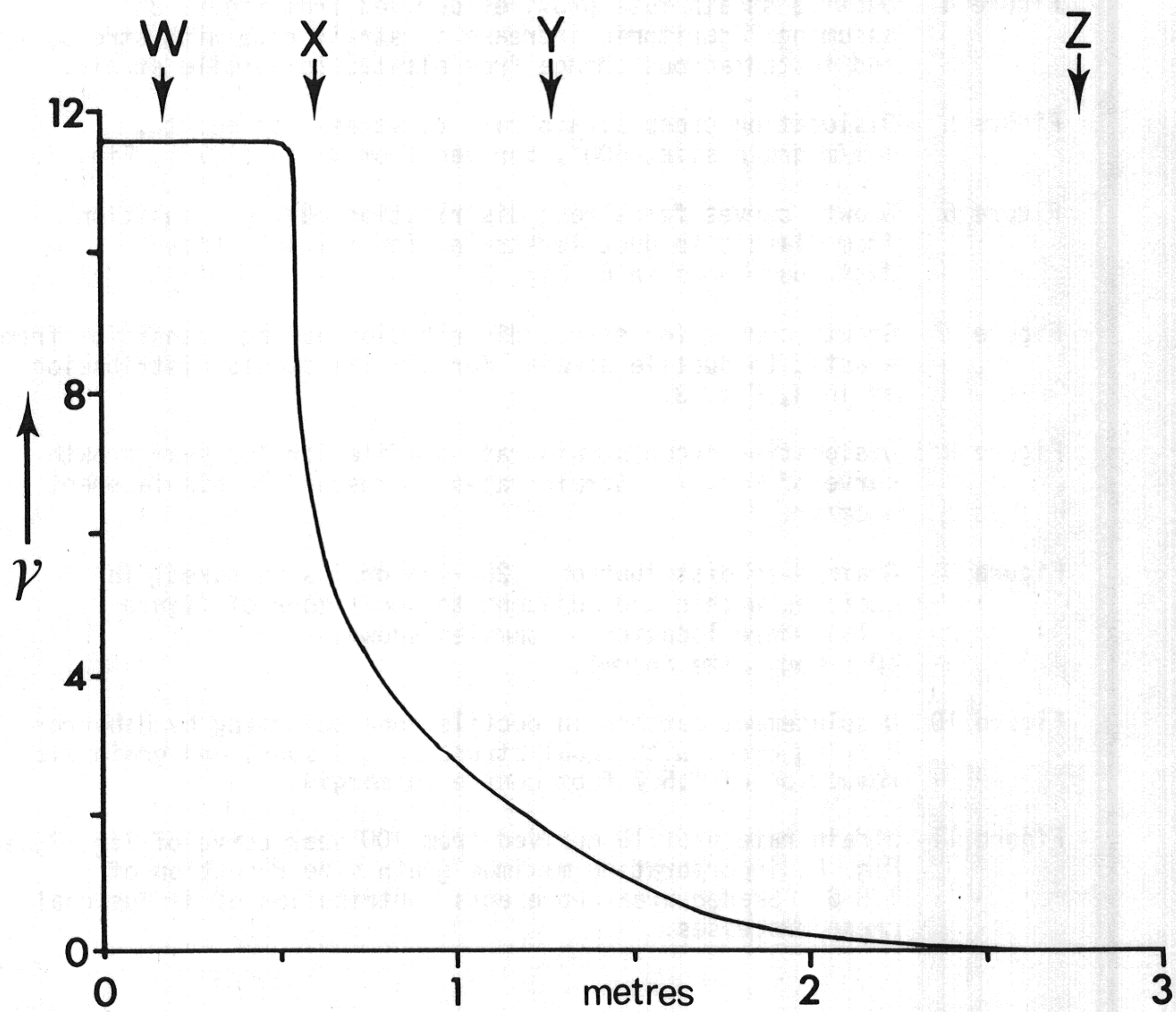
Figure 8 Dislocation creep strain rate profile for 100 year growth curve of Fig. 7. Strain rates correspond to displacement 5 cm/yr.

Figure 9 Grain size distributions (200-500 grains measured) in gneisses within and adjacent to shear zone of figure 1 (a) where location of samples shown. (Ø = Log_2 size in mm).

Figure 10 Displacement pattern in ductile zone deforming by Nabarro-Herring creep with equal stress across zone, and grain size reduction of 1.5 Ø from centre to margin.

Figure 11 Strain rate profile derived from 100 year curve of Fig. 7, and Fig. 8, incorporating maximum grain size reduction of 1.5 Ø. Shaded area represents contribution of diffusional creep processes.

FIGURE 1(a)



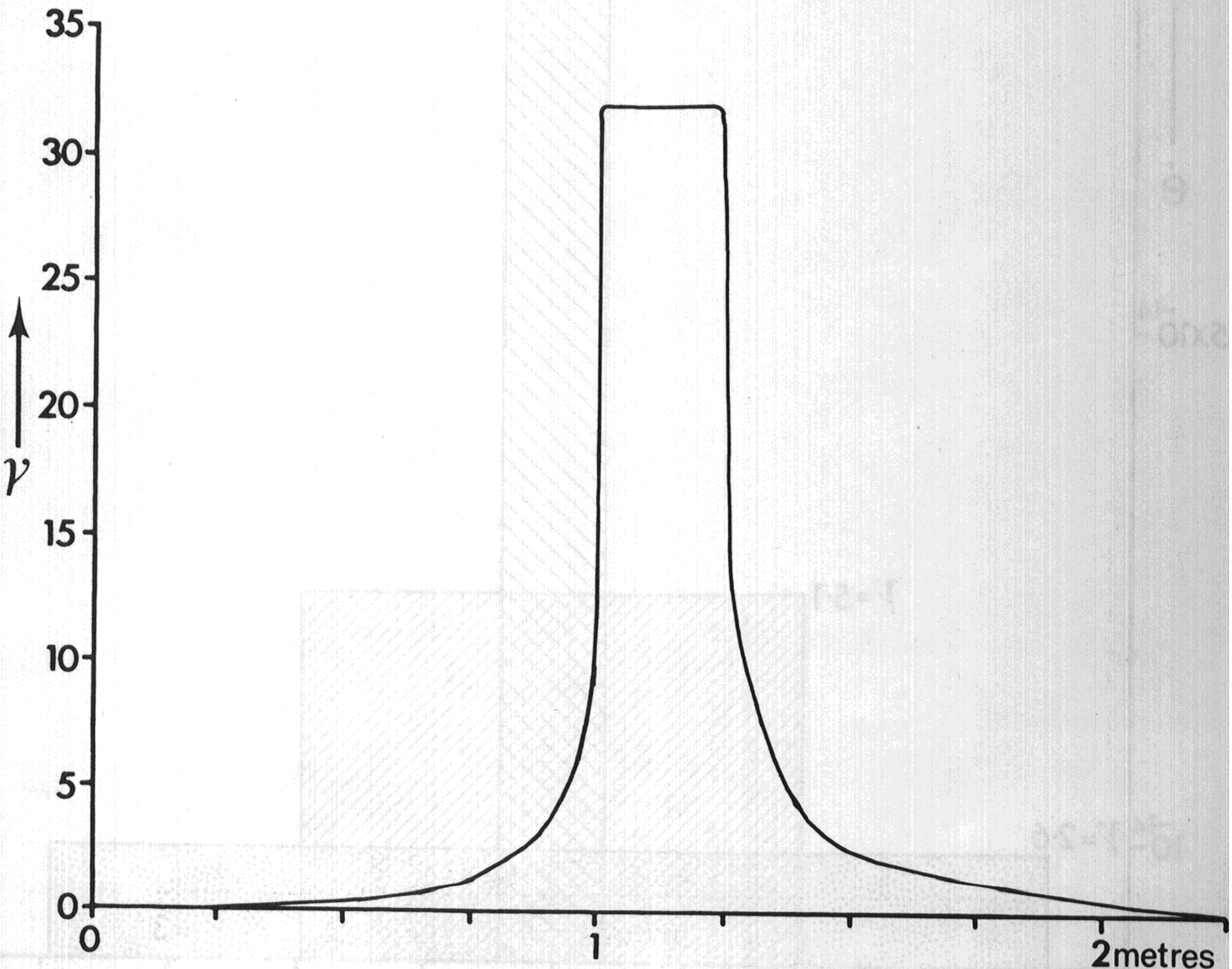
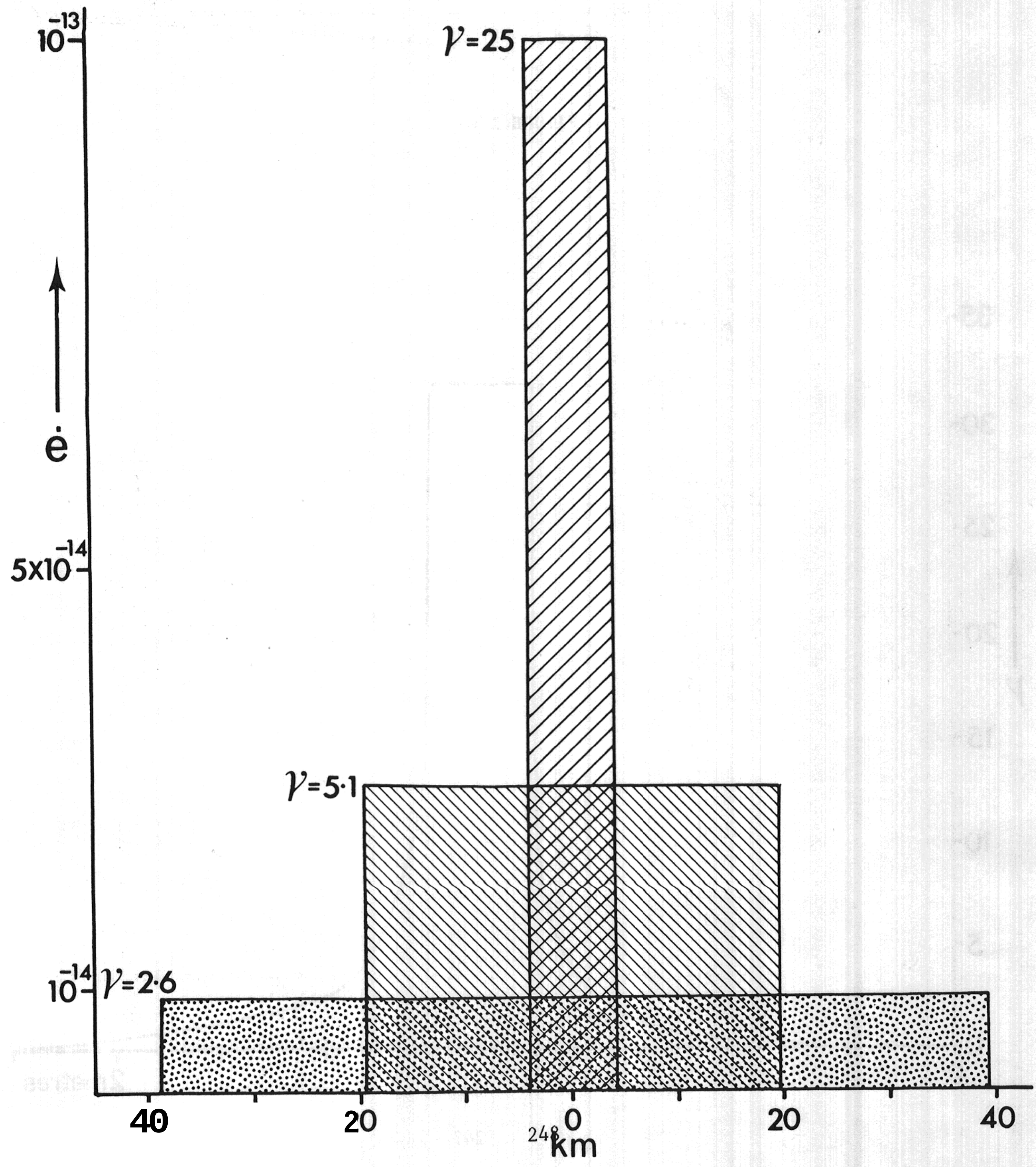
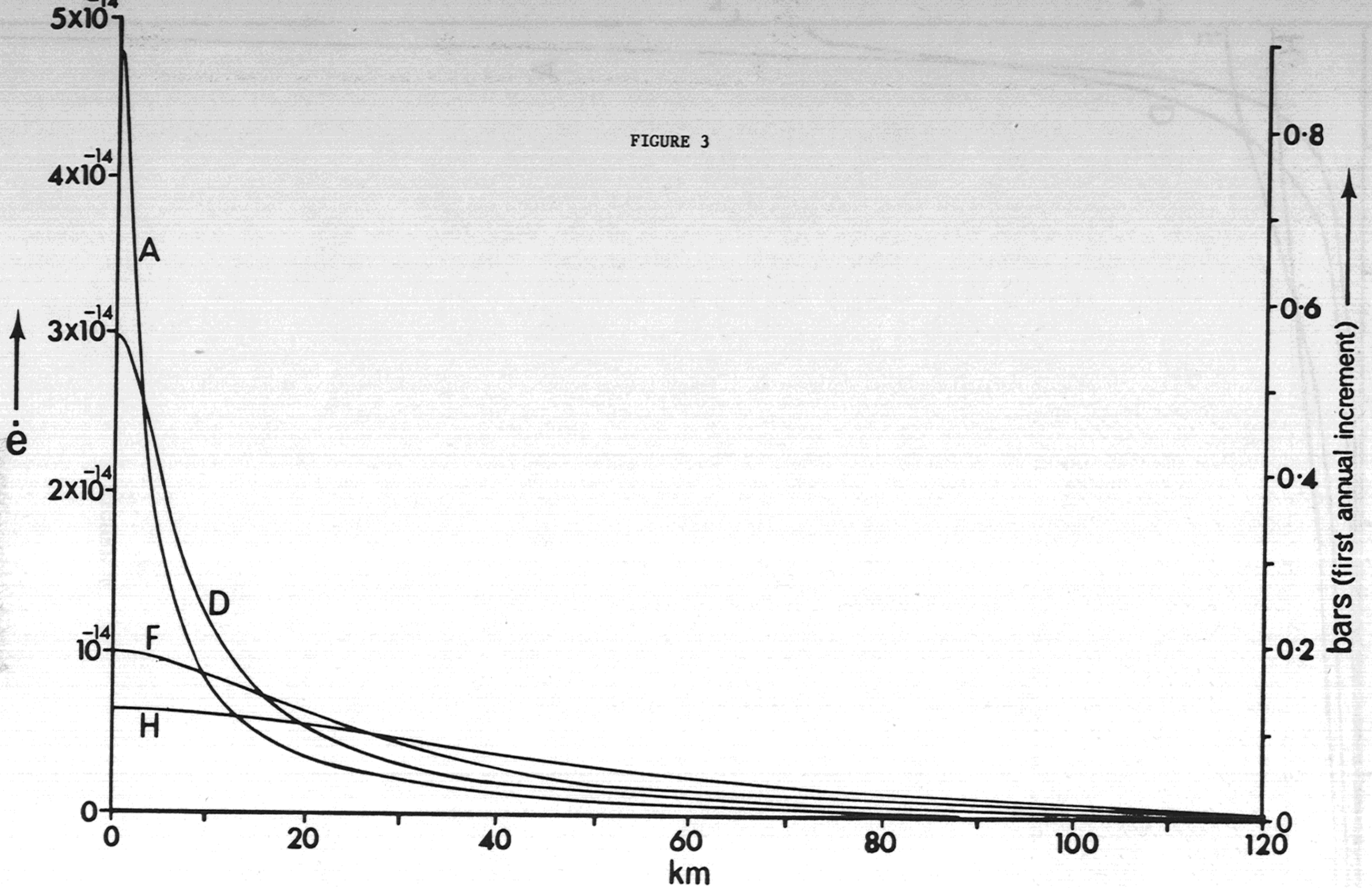

35
30
25
20
15
10
5
0
ν
0
1
2metres

FIGURE 2



10^{-13}
$\gamma=25$
$\dot{e}$
5×10^{-14}
$\gamma=5{\cdot}1$
10^{-14}
$\gamma=2{\cdot}6$
40
20
0
20
40
km

FIGURE 3



5×10^{-14}
4×10^{-14}
3×10^{-14}
2×10^{-14}
10^{-14}
0
$\dot{e}$
A
D
F
H
0
20
40
60
80
100
120
km
0·8
0·6
0·4
0·2
0
bars (first annual increment)

FIGURE 4

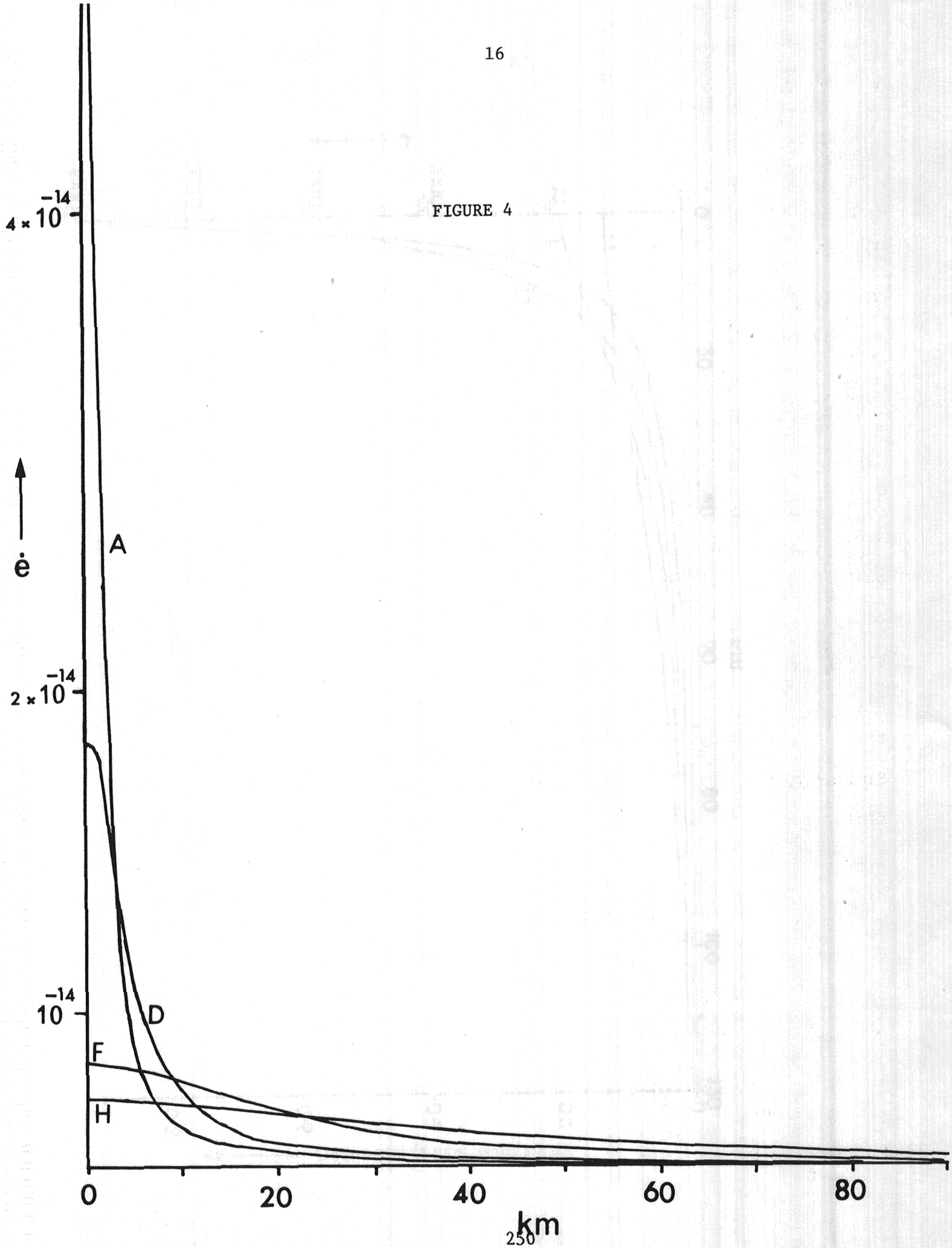


FIGURE 5

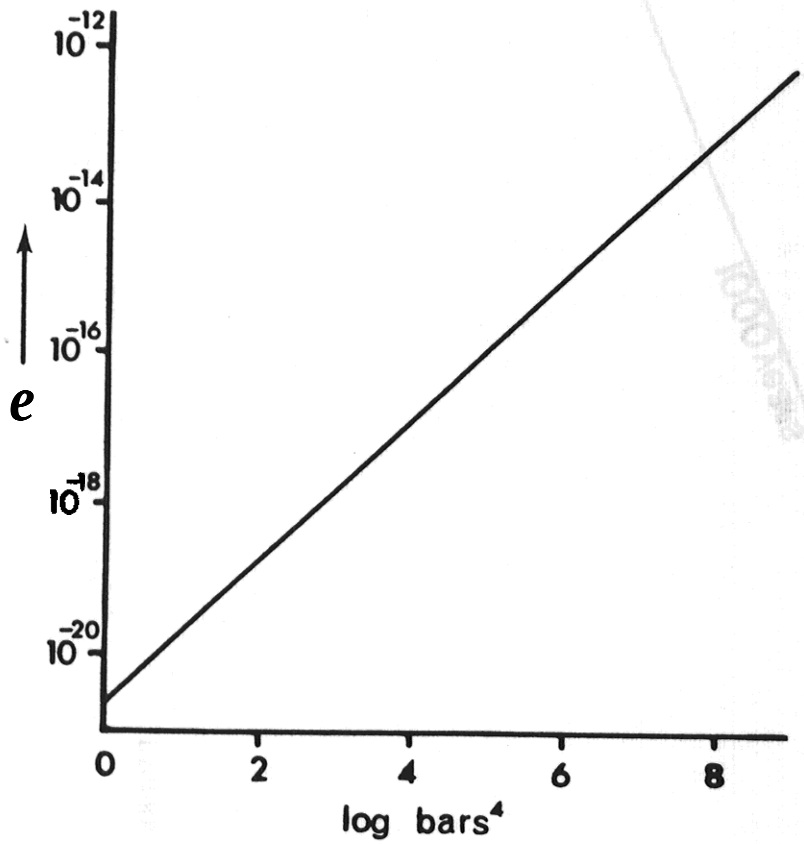
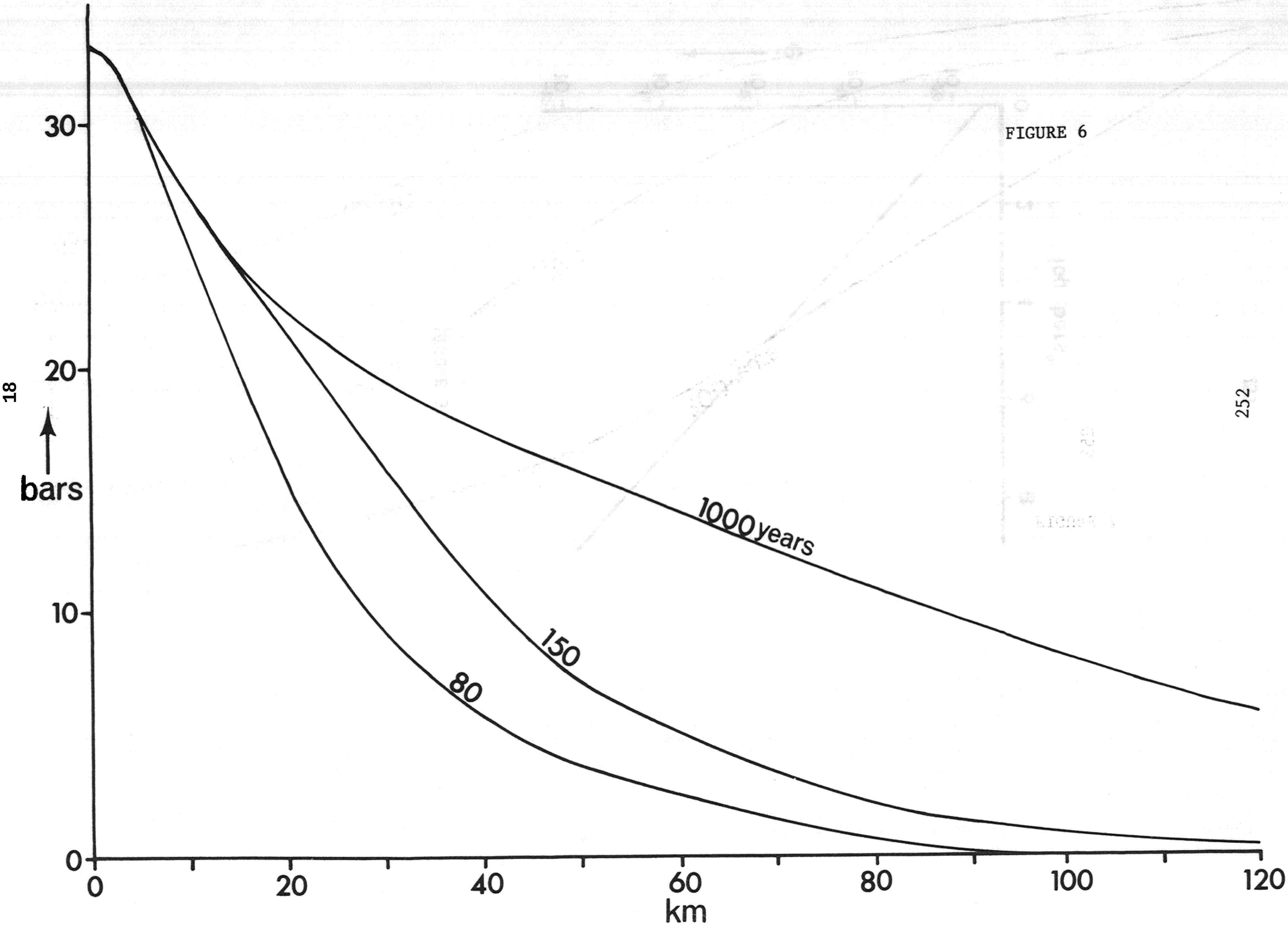


FIGURE 6



19

FIGURE 7

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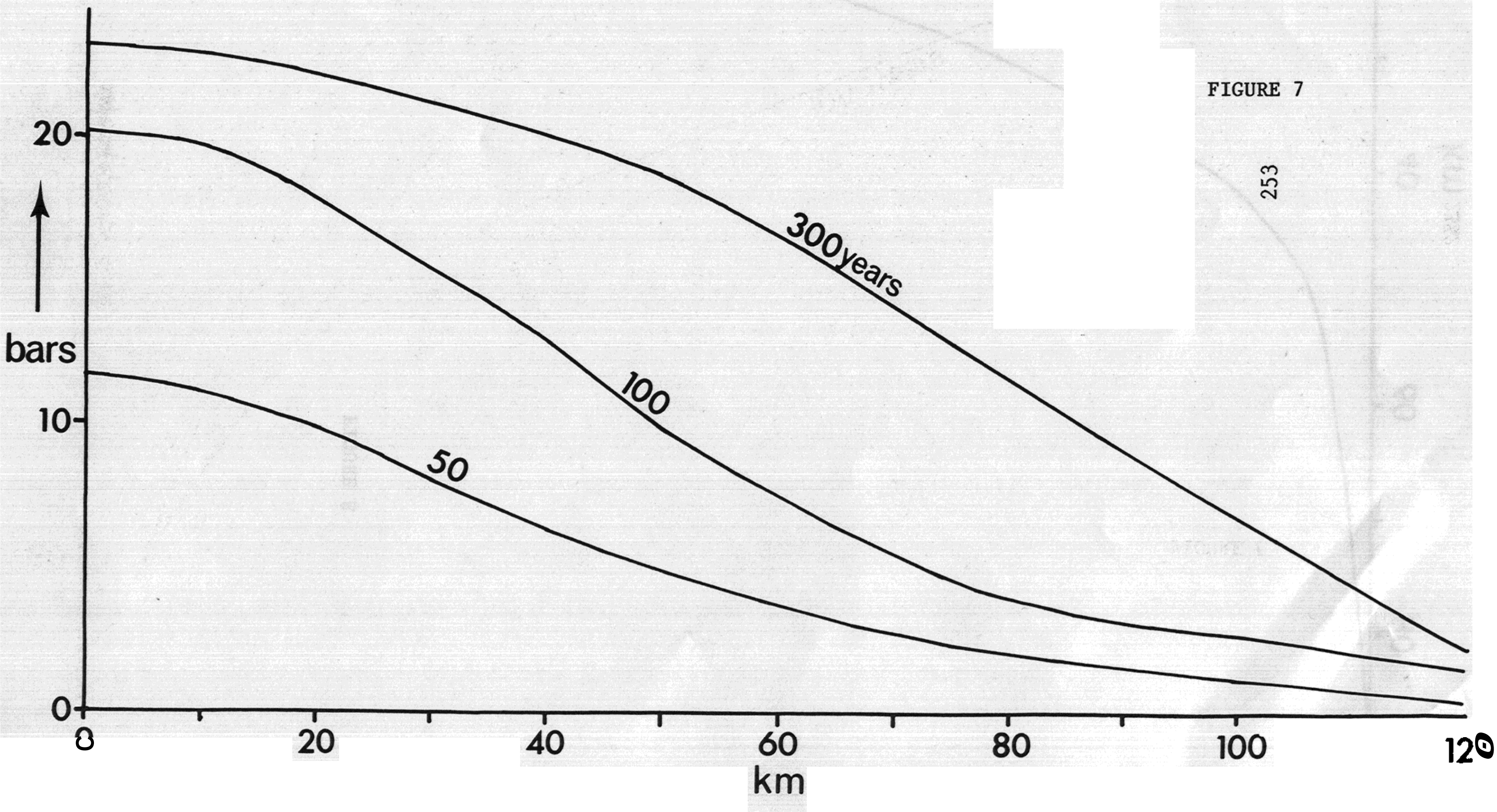
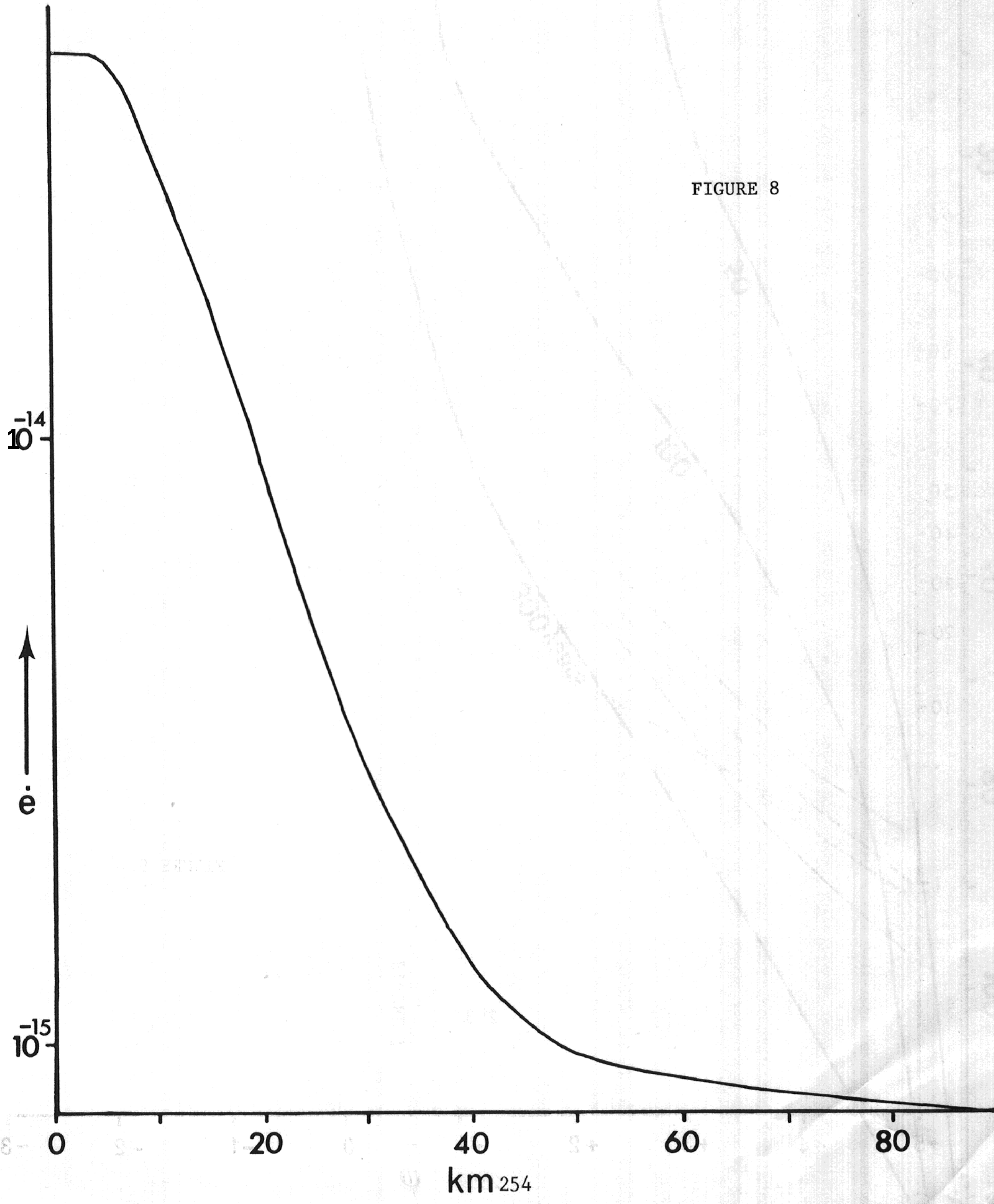


FIGURE 8



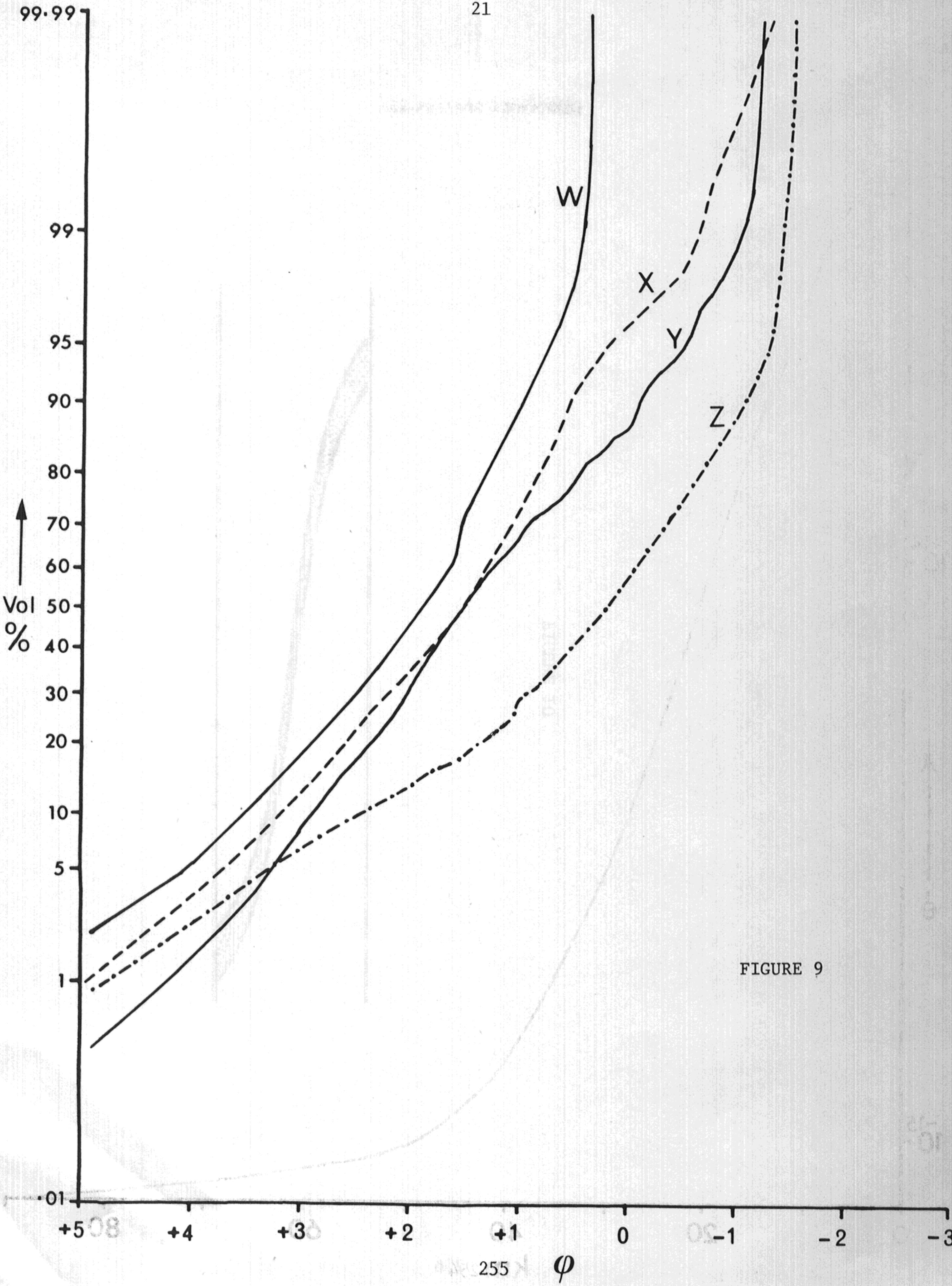


FIGURE 9

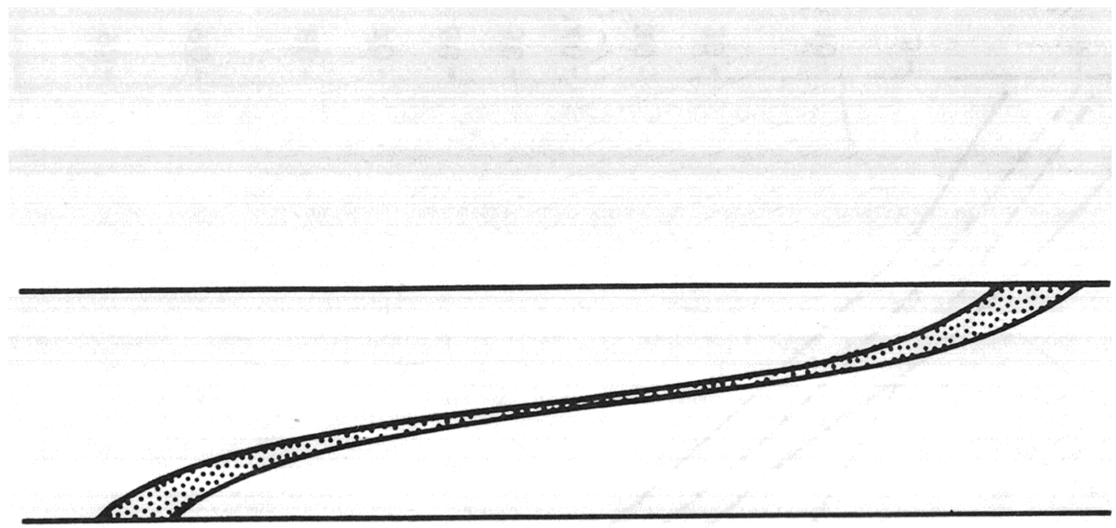


FIGURE 10

FIGURE 11